

# Changes In Physical-Chemical Properties Of Clay Under Compression

Seredin V.V., Rastegayev A. V., Panova E. G., Medvedeva N. A.

**Abstract**— It has been determined experimentally that the content of loosely bound and strongly bound water and hydroxyl groups and the mass recrystallization of minerals is controlled not only by the composition, structure and properties of the crystal lattice of montmorillonite and kaolinite clays, but also by the pressures under which the clay sample had been formed.

**Index Terms**— clay, pressure, mass loss, thermal analysis, x-ray phase analysis.

## I. INTRODUCTION

The durability of industrial and civil objects depends mainly on the strength and deformation properties of soils which form their base. At the same time, the calculated values of mechanical properties, on the one hand, largely depend on the technogenic load on the subgrade [Seredin and all, 2015], and on the other hand, on the content of bound water in the soils, especially in clay soils. The state of bound water in clays have been studied by many Russian and foreign scientists. Some researchers describe the influence of clays mineral composition, their initial moisture and composition of exchangeable cations on the thermal dehydration of bound water [Tang L., 1993; Fredlund D.G., 2010; Stefani V.F., 2014; Batistella M., 2015; Sun D., 2015].

The data on the influence of particle size on the dehydration curves are presented in [Cora I., 2014]. It reveals that the smaller size of clay particles causes the sharper divergence of the dehydration curves at high temperatures. It is concluded that there is no significant difference in the values of energies corresponding to the active centers of the basal facets and chipped crystals.

Changes in the properties of bound water in clays under high temperatures and pressures were studied in [Zlochevskaya, 1977; Kuprin, 2002; Lepoitevin M., 2014]. According to the authors, at the compaction of water-saturated clays the free water of large pores is removed foremost, then at 1-3 MPa osmotic water is removed, and at pressure more than 10 MPa starts the removing of structured hydration layers of the adsorption-bound water. According to some authors [Xia Bian, 2016] the closest to a solid surface water layers which determine the moisture of clays are not squeezed at tens of MPa, and mono-layers - at hundreds of MPa.

However, despite the considerable scientific and practical importance of the problem there is a lack of experimental studies. Comparative analysis of compressive stability of various in mineral composition clays and, therefore, the structural types may present a particular interest.

The aim of this work was to study the patterns of changes in the content of bound water in clays at high pressures. The task of the investigation was: 1) to study the effect of pressure on granulometric composition and mass loss of bound water in kaolinite and montmorillonite clays; 2) to develop a mathematical model that can predict the mass loss of bound water in a clay at various pressures.

**Samples, analytical method and procedures.** The study was carried out on the samples of kaolinite and montmorillonite clays. Shearing high pressure device was specially constructed for the experiment (Fig.1). The working surfaces of the device (pos.3 Fig.1) are of hard alloy material with the area of  $S=0,75\text{cm}^2$ . Press PLG-20 was applied as a loading device.

Granulometric composition was determined according the method based on the measurement of particles using laser device Analysette-22 (Fritsch, Germany).

Thermal analysis (DSC/TG) of the samples was carried out on synchronous thermoanalyzer STA 409 PC Luxx (Netzsch-Geratebau GmbH). Sample after grinding was placed in a corundum crucible and heated to the temperature of  $1000^\circ\text{C}$  at a rate of  $10^\circ\text{C}$  per minute. The results of thermal analysis are recorded on thermograms which reflect the changes mass loss (m %) of the initial sample along the heating curve (TG). Analysis of the thermal curves was performed using the published data [Kuprina, 1973].

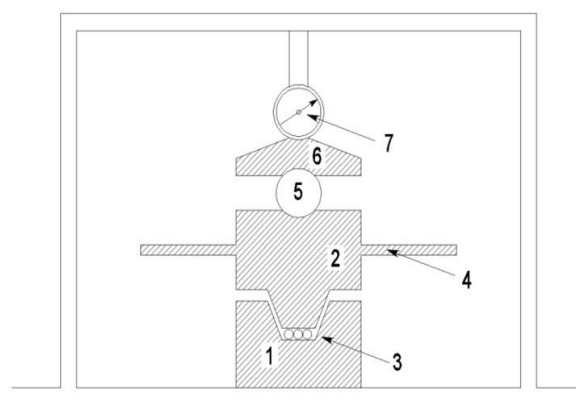


Fig. 1. High pressure device for studying soil shearing.

1- lower holder; 2- upper holder; 3- zone of soil shearing with the area of  $0.75\text{ cm}^2$ ; 4- handles to rotate the upper holder (soil shearing); 5- centering ball; 6- the upper plate of the loading device (press); 7- device for fixing the transferred load onto the soil.

X-ray phase analysis of samples was performed using X-ray powder diffractometer D2 Phaser "Bruker" with the following

characteristics: X-ray tube with copper anode (radiation  $\text{CuK}\alpha$ ,  $\lambda=1,54060 \text{ \AA}$ ), generator tension of 30 kV, amperage – 10 mA; the linear detector LYNXEYE; filter – Ni.

Representative sample was grinded with alcohol in an agate mortar to the size of particals about 20-40 mkm. The powdered sample was placed into a cuvette for X-ray diffraction. Conditions were the following: divergent slit of 0,2 mm, Soller slits: the primary -  $2,5^\circ$ , the secondary -  $2,5^\circ$ ; the angular range from 5 to  $70^\circ 2\theta$ ; speed dialing pulses at each point 1.0 s, step -  $0,02^\circ$ . Oriented samples were studied in the interval from 4 to  $35^\circ 2\theta$ .

Oriented samples were made from aqueous suspensions of clay fraction by sedimentation onto the defatted glass slides and then dried at room temperature. One sample (air-dry) was studied by X-ray diffraction, the other two underwent additional processing: saturation with glycerin during the day, calcination in a muffle furnace for 1 hour at a temperature of  $600^\circ\text{C}$ . Program Diffrac Eva was applied for curve handling, measurement of peak width at mid-height and the peak area (integral intensity) of the reflections of the clay minerals.

Experimental study of water content (mass) in the clay under high pressures was carried out by stages. At the first stage mineral composition of the initial soil was studied by X-Ray phase analysis. At the second stage the clay samples were prepared for thermal and granulometric analyses. To do this, the initial clay soil was placed in a mortar and powdered. The powdered soil was put into a paper bag and stored at  $t=25^\circ\text{C}$  and relative humidity  $\text{RH}=70\%$ .

Then, the sample about 0.5g was placed into the shearing zone of the device. After that, vertical pressure was transferred onto the soil by press in the following way: the first stage - initial soil,  $P=0 \text{ MPa}$ , at the second stage the vertical pressure was 300MPa, at the third stage it was 600MPa, at the fourth – 1000MPa, at the fifth – 1200MPa, at the sixth – 1500MPa, at the seventh – 1800MPa, and at the eighth - 2000MPa.

Properties of a series of samples of montmorillonite and kaolinite clays after the experiments, were studied by means of thermogravimetric, granulometric and X-ray analyses.

## II. RESULTS AND DISCUSSION

*Properties of the initial clays.* According the results of X-ray phase analysis the montmorillonite clay is composed of montmorillonite (75%), kaolinite (3.6%), quartz (11.4%), albite (6.7%), calcite (3.3%). Kaolinite clay contains of kaolinite (76.7%), montmorillonite (15.6%), quartz (7.7%). Hygroscopic moisture (weight) for the montmorillonite clay was  $W=5.4\%$ , and for the kaolinite clay  $W=3.0\%$ .

*Changes in granulometric composition of clays in dependence on pressure.*

Results of the experimental studies are presented in Table 1 and Figures 2 and 3. Data in Table 1 show that in the initial samples of kaolinite clay fraction  $<1 \text{ mkm}$  ( $F_{<1}$ ) makes up 13.9%, fraction 1-5 mkm ( $F_{1-5}$ ) – 51.9%, fraction 5-50mkm ( $F_{5-50}$ ) – 34.2%.

Table 1. Average values of the fractional composition of clays (size of structural element in  $\mu\text{km}$ )

Pressure, P, MPa	Sample №	Montmorillonite clay*				Sample №	Kaolinite clay			
		Fraction, %					Fraction, %			
		<1	1-5	5-50	>50		<1	1-5	5-50	>50
0	1a	10,5	46,0	43,4	0,1	2a	13,9	51,9	34,2	0,00
300	1ab <sub>1</sub>	7,3	39,5	53,2		2ab <sub>1</sub>	12,8	45,7	41,5	
600	1ab <sub>2</sub>	6,2	36,0	57,8		2ab	10,6	39,8	42,4	
1000	1b	5,8	36,2	58,0		2b	12,9	48,3	38,8	0
1500	1c	17,1	51,8	31,1		2c	10,7	44,0	32,3	13,0
1800	1c <sub>1</sub>	14,1	48,2	47,7		2c <sub>1</sub>	10,1	41,8	48,1	
2000	1d	8,2	26,2	65,6		2d	10,0	37,2	52,8	0,0

\* data from [Chikov, 1989].

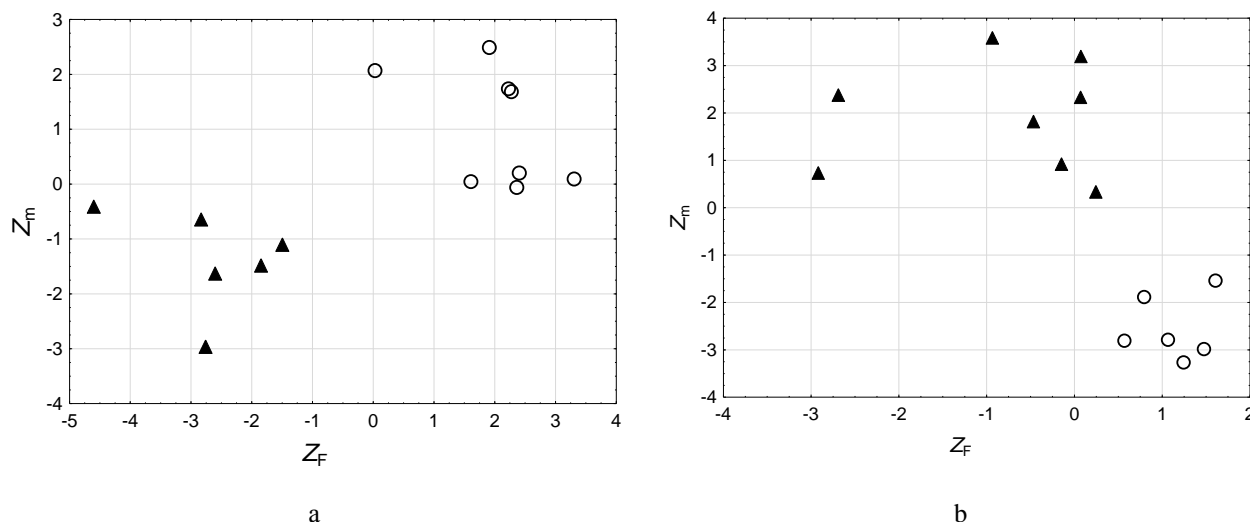


Fig. 2. Dependence between  $Z_F$  and  $Z_m$  for montmorillonite (a) and kaolinite (b) clays. Circles -  $P < 1000 \text{ MPa}$ ; triangles -  $P > 1000 \text{ MPa}$ .

With pressure increasing up to  $P=1000\text{MPa}$  takes place the decrease of  $F_{<1}$  up to 10.6%,  $F_{1-5}$  up to 39.8% and increase of  $F_{5-50}$  up to 42.4%. At  $P=1000\text{MPa}$  in the clay increases the content of  $F_{<1}$  up to 12.9%,  $F_{1-5}$  up to 48.3%, decreases the content of fraction  $F_{5-50}$  up to 32.3% and takes place the formation of fraction  $F_{>50}$  which corresponds to 13%. With further pressure increasing up to  $2000\text{MPa}$  the content of  $F_{<1}$

and  $F_{1-5}$  decreases up to 10% and 37.2% correspondently and  $F_{5-50}$  increases up to 52.8%. So, with pressure increasing the studied soils demonstrate the decrease of clay fraction and the increase of dust size fraction. At pressures  $P=600\div 1000\text{MPa}$  the kaolinite clay shows considerable increase of clay fractions. Thus, these pressures are the marginal in the formation of the granulometric composition of this clay.

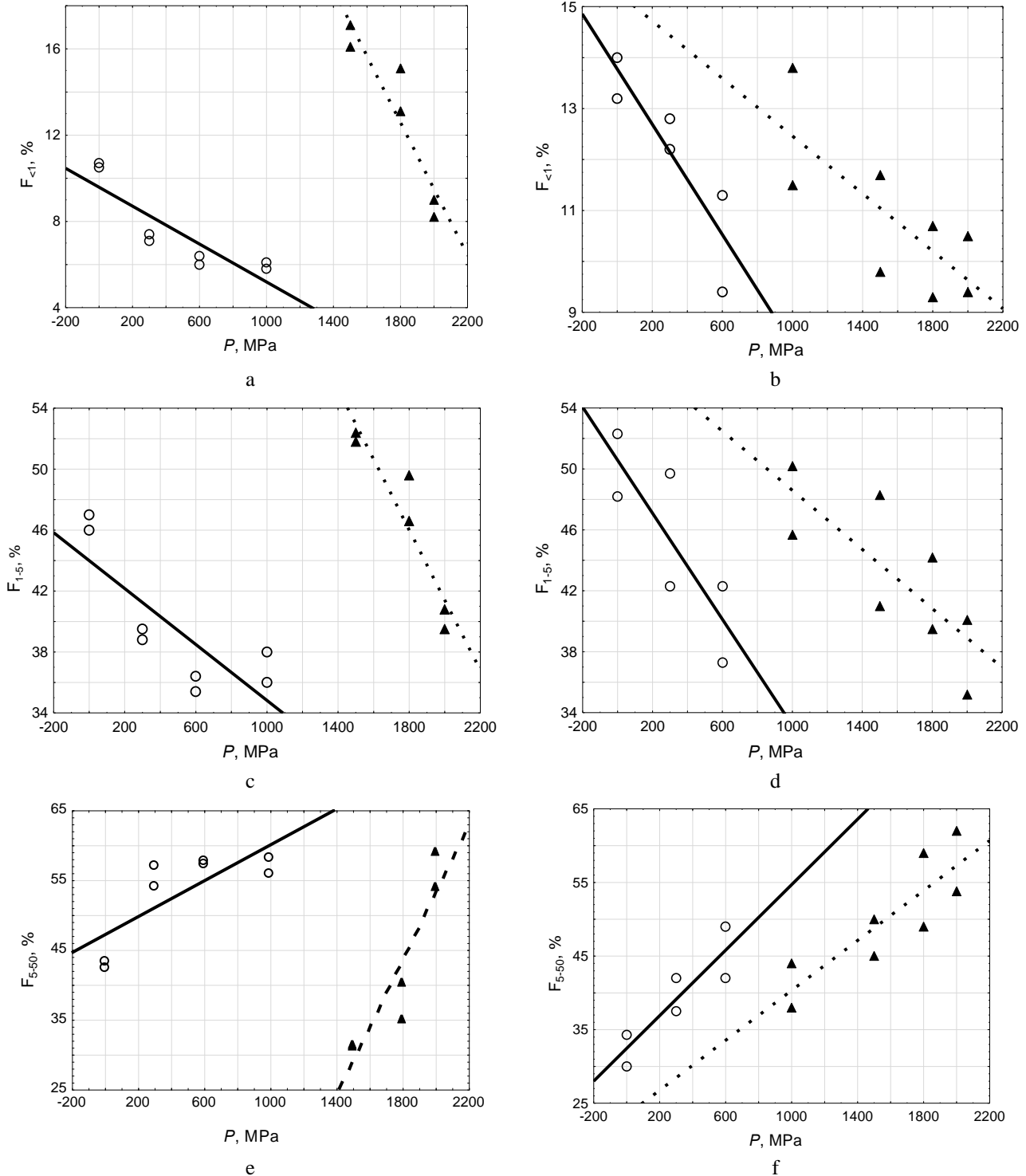


Fig. 3. Dependence between the pressure ( $P$ ) and granulometric composition ( $F$ ) for montmorillonite (a, c, e) and kaolinite (b, d, f) clays. Circles -  $P < 1000\text{MPa}$ ; triangles -  $P > 1000\text{MPa}$ .

It is established that the marginal pressures determining the formation of the fractional variety of kaolinite clays ( $R=600\div 1000\text{MPa}$ ) are less than for the montmorillonite clay ( $R=1000\div 1500\text{MPa}$ ).

Statistical methods were applied to the experimental data to prove the conclusion about the different conditions for formation of clays granulometric composition at pressures up

to  $P < 1000 \text{ MPa}$  (grade 1) and  $P > 1000 \text{ MPa}$  (grade 2). Two discriminant functions were compiled for the kaolinite clay:

-the first function ( $Z_F$ ) is compiled by the indicators of granulometric composition:

$$Z_F = 24,97363 - 0,50076 F_{<1} - 0,15606 F_{1-5} - 0,27302 F_{5-50}$$

at multidimensional centers of groups  $Z_{F1} = 1,127995$  and  $Z_{F2} = -0,845996$ .

-the second function ( $Z_m$ ) is compiled by the data characterizing the mass loss of bound water:

$$Z_m = 4,05836 - 1,31072 m_l + 11,27941 m_{st} - 0,51574 m_{ms} - 1,75383 m_{OH} + 0,10949 m,$$

at multidimensional centers of groups  $Z_{m1} = -2,54669$  and  $Z_{m2} = 1,91002$ .

The mass loss for each category of bound water are: loosely bound water of the colloid surface (LWC) -  $m_l$ ; strongly bound water of the colloid surface (SWC) -  $m_s$ ; water of the mineral surface and the hydration of ions (WMS) -  $m_{ms}$ ; water of the hydroxyl groups in the mineral (WHM) -  $m_{OH}$ ; total mass loss of the bound water was determined ( $m$ ).

The calculations by the discriminant functions showed that correct recognition of the sample selection is 100%, as illustrated in Fig.2. So, the marginal value of pressure ( $P=1000 \text{ MPa}$ ) for kaolinite clay, which divides the sample into two classes, was chosen reasonably.

Correlation and regression analyses were applied to assess the effect of pressure on the granulometric composition of the clays. The correlation fields are presented in Fig. 3. They show that with the increase of pressure in grade 1 and grade 2 the content of clay fractions,  $F_{<1}$  and  $F_{1-5}$  decreases and the content of dust fraction  $F_{5-50}$  increases.

The changes in granulometric composition of clay soils may be caused by mechanical processes of crushing as well as by physical-chemical features, for example, by the forces of attraction and repulsion of clay particles. Such possibility was

mentioned in the theoretical publications [Deryagin, 1985; Enikolopyan, 1986]. According the theory the forces of molecular attraction and electrostatic repulsion occur between the particles when they draw closer to each other. Thus, depending on the distance between the particles several potential minima and barriers are formed.

With pressure increase from 0 up to  $1000 \text{ MPa}$  there takes place the further decrease of distance between the clay particles causing the formation of electrostatic forces of repulsion (formation of the first potential barrier) which are realized in the process of particles dispersion. So, at this pressure the amount of clay fraction increases sharply and the amount of dust fraction decreases. In addition, at these pressures the effects of mechanical processes superimpose over the physical-chemical processes that causes fragmentation of dust fraction noted by a number of authors. Further pressure increase  $P > 1000 \text{ MPa}$  also results in the decrease of distance between the particles and formation of molecular forces of repulsion (formation of the close potential barrier) causing the aggregation of particles proved by the experiment (Fig. 3).

Comparison of pressures at which the potential barriers of repulsion are formed (first potential barrier) showed that the barrier in the kaolinite clay is formed at lower pressure ( $P=600 \div 1000 \text{ MPa}$ ) than in the montmorillonite clay ( $P=1000 \div 1500 \text{ MPa}$ ). This is probably due to the size and amount of clay colloids in the studied soils. The content of the particles with the size less than  $5 \mu\text{m}$  in the kaolinite clay corresponds to 65,8%, and in the montmorillonite it corresponds to 56.5%.

Correlation analysis demonstrated that there are statistical links between the granulometric composition of clays and pressure proved by significant correlation coefficients (Table 2).

Table 2. Results of statistical analysis between the pressure (P) and granulometric composition for montmorillonite and kaolinite clays.

Name of the clay	Fractions, $\mu\text{km}$	P<1000MPa			P>1000MPa		
		$F_{<1}$	$F_{1-5}$	$F_{5-50}$	$F_{<1}$	$F_{1-5}$	$F_{5-50}$
Kaolinite clay	Correlation coefficient	-0,89	-0,82	0,89	-0,76	-0,78	0,85
	Standard deviation	1,63	5,63	6,68	1,49	4,99	7,97
Montmorillonite clay	Correlation coefficient	-0,87	-0,81	0,77	-0,92	-0,93	0,91
	Standard deviation	1,98	4,46	6,53	3,73	5,54	11,93

The presence of the identified links enables to calculate the mathematical models to predict the change of granulometric composition of kaolinite clays depending on pressure.

For the fraction less than  $1 \mu\text{km}$  the regression equation has the form:

$$\text{Grade 1 } F_{<1} = 13.775 - 0.0054P$$

$$\text{Grade 2 } F_{<1} = 15.2815 - 0.0028P$$

For the fraction 1-5  $\mu\text{km}$  the regression equation has the form:

$$\text{Grade 1 } F_{1-5} = 50.575 - 0.0174P$$

$$\text{Grade 2 } F_{1-5} = 58.2963 - 0.0097P$$

For the fraction less than 5-50  $\mu\text{km}$  the regression equation has the form:

$$\text{Grade 1 } F_{5-50} = 32.4583 + 0.0223P$$

$$\text{Grade 2 } F_{5-50} = 23.4013 + 0.017P$$

It should be noted that these equations are reliable under the conditions of the carried out experiment.

*Change of bound water mass loss in dependence of the pressure*

Thermal analysis gave us possibility to registrate water mass loss.

Thermograms gave quantitative information on the mass loss for each category of bound water: loosely bound water of the colloid surface (LWC) -  $m_l$ , strongly bound water of the colloid surface (SWC) -  $m_s$ , water of the mineral surface and the hydration of ions (WMS) -  $m_{ms}$ , water of the hydroxyl

groups in the mineral (WHM) -  $m_{OH}$ . Then total mass loss of the bound water was determined ( $m$ ). The term “mass loss”, should be understood as the decrease of the mass of a substance relatively the starting mass of the sample, in percent.

The study was carried out in several stages.

*The first stage* concerned the influence of pressure on the water mass loss ( $m$ ). The results are presented in Fig. 4. Analysis of correlation fields between the mass loss and the pressure over the soil demonstrates that there are two groups divided by the boundary at  $P=1000$  MPa. Basing on this fact it was decided to conduct subsequent processing of the experimental data for the two groups separately. The first group included the data obtained at pressures  $P \leq 1000$  MPa (Grade 1) and the second  $P > 1000$  MPa (Grade 2).

*Kaolinite clays.* Figure 4 demonstrates that in Grade1  $m_l$  increases with the pressure increase, at the same time there is no influence of pressure on the  $m_s$ , and  $m_{ms}$  and  $m_{OH}$  decrease. In Grade2 there is a different pattern: the mass loss of all types of bound water decrease with the pressure increase.

*Montmorillonite clays.* In Grade 1 the mass losses of all types of bound water increase with the pressure increase. In Grade 2 the mass loss of  $m_l$  decreases with the pressure increase but at the same time the  $m_s$ ,  $m_{ms}$  and  $m_{OH}$  increase.

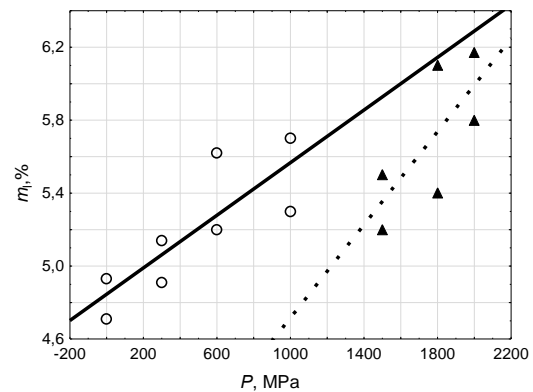
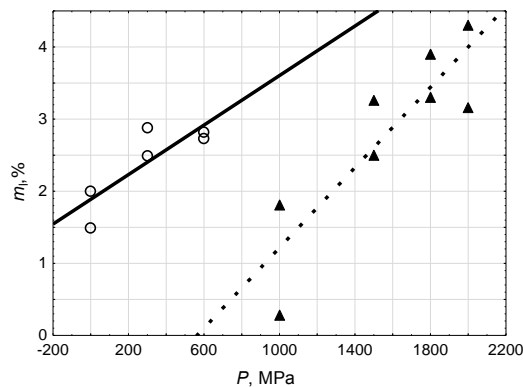
Comparison of the mass losses for the studied clays showed that the influence of pressure on the formation of colloid loose bound water is similar in both kaolinite and montmorillonite clays. With the pressure increase the  $m_l$  increases in Grade 1 and decreases in Grade 2.

A different pattern is observed for the colloid strongly bound water. In the kaolinite clay the  $m_s$  remains unchanged in Grade 1 with the pressure increase and decreases in Grade 2. In the montmorillonite clay, on the contrary, the  $m_s$  increases in Grades 1 and 2 with the pressure increase.

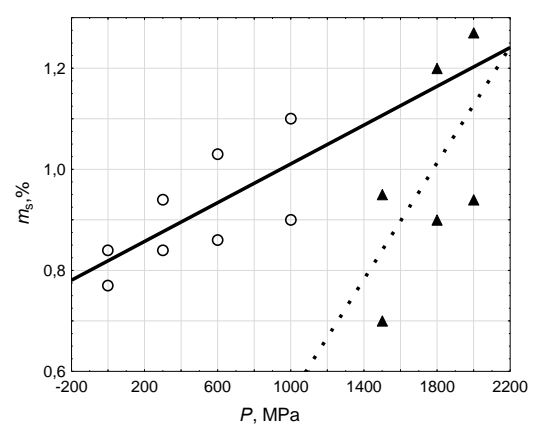
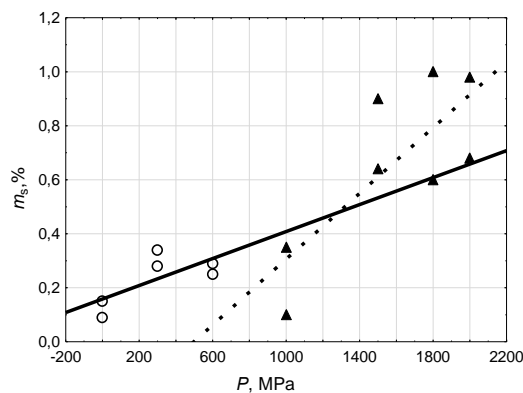
The mineral surface water and hydroxyl water in the kaolinite clay demonstrate the decrease of the  $m_{ms}$  and  $m_{OH}$  with the pressure increase and in the montmorillonite clay, on the contrary, these parameters increase.

Thus, on a qualitative level, we can assume that the pressure has a mixed effect on the formation of the  $m_s$ ,  $m_{ms}$  and  $m_{OH}$  in the kaolinite and montmorillonite clays.

Correlation analysis was applied to quantify the effect of pressure on the change of mass losses of bound water in the studied clays. The results are presented in Table 3. Critical values of the coefficients of pair correlation were calculated basing on the size of selection and reliability of the obtained results. For the first group the critical value of the correlation coefficient is  $r_k = 0,71$   $K=6$  degrees of freedom  $\alpha=0,05$  significance level, and for the second group -  $r_k = 0,81$   $K=4$  degrees of freedom  $\alpha=0,05$  significance level.



a



b

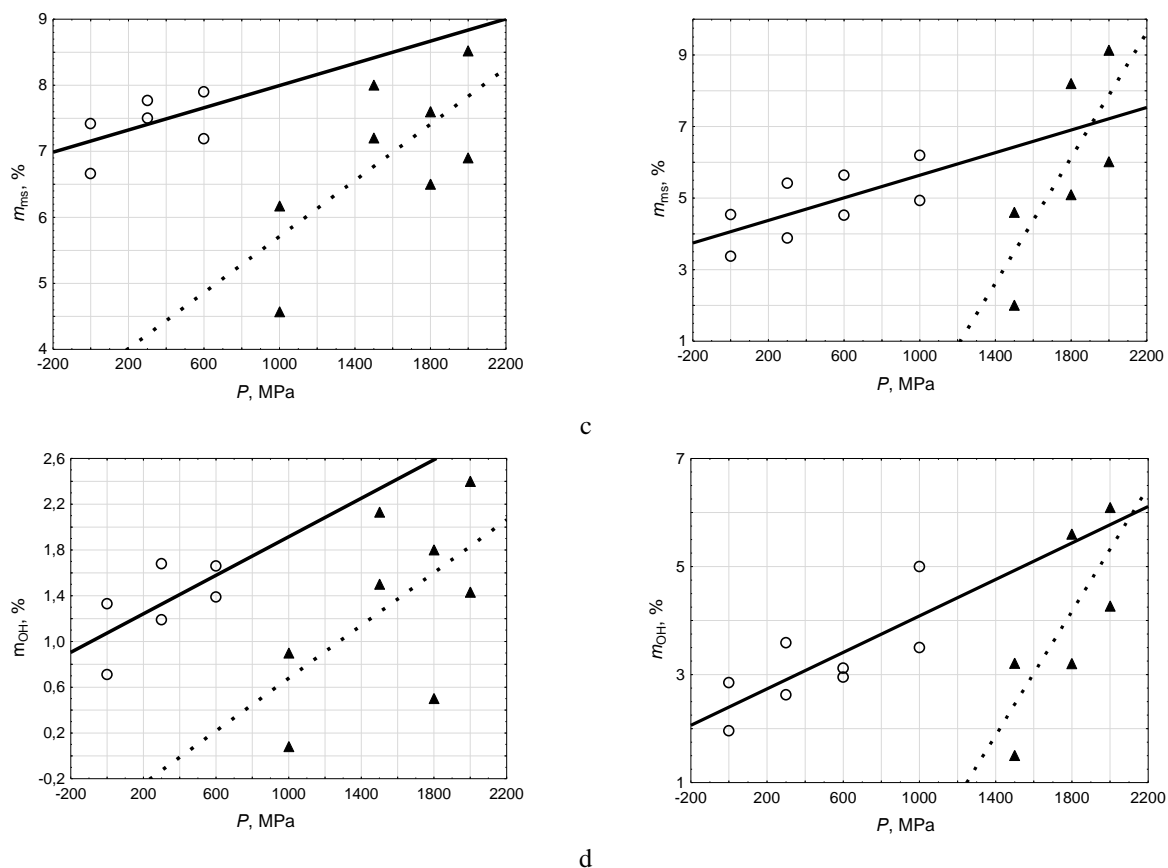


Fig.4. Correlation fields between pressure (P) and mass loss of the bound water (m) for montmorillonite (right column) and kaolinite (left column) clays.

a –  $m_l$  - loosely bound water of the colloid surface; b –  $m_s$  - strongly bound water of the colloid surface;  
c –  $m_{ms}$  - water of the mineral surface and the hydration of ions; d –  $m_{OH}$  - water of the hydroxyl groups in the mineral. Circles -  $P < 1000$  MPa; triangles -  $P > 1000$  MPa.

The data (Table 3) show that in Grade 1 of the montmorillonite clay there are statistical links between the mass loss of the loose bound ( $r = 0.77 > r_k = 0.71$ ), strongly bound ( $r = 0.75 > r_k = 0.71$ ) colloid waters and the pressure. In Grade 2 such links are determined between the pressure and

the  $m_{ms}$  ( $r = 0.89 > r_k = 0.71$ ) and also between the pressure and the  $m_{OH}$  ( $r = 0.90 > r_k = 0.71$ ). Thus, we can conclude that the formation of water in the colloid is controlled by the pressure of up to  $P < 1000$  MPa, and in the crystal  $P > 1000$  MPa.

Table 3. Correlation matrix of physical-chemical clays properties

Clay	Charac teristic	P<1000MPa				P>1000MPa			
		$m_l, \%$	$m_{st}, \%$	$m_{ms}, \%$	$m_{OH}, \%$	$m_l, \%$	$m_{st}, \%$	$m_{ms}, \%$	$m_{OH}, \%$
Montmorillonite clay	$\sigma, \text{ MPa}$	0,77	0,75	0,27	0,22	-0,50	0,46	0,89	0,90
	$m_l, \%$	1,00	0,67	0,48	0,60	1,00	0,41	-0,07	-0,09
	$m_{st}, \%$		1,00	0,23	0,12		1,00	0,73	0,76
	$m_{ms}, \%$			1,00	0,85			1,00	0,91
	$m_{OH}, \%$				1,00				1,00
Kaolinite clay	$\sigma, \text{ MPa}$	0,82	0,07	-0,77	-0,59	-0,46	-0,57	-0,58	-0,83
	$m_l, \%$	1,00	0,45	-0,59	-0,72	1,00	0,88	0,30	0,21
	$m_{st}, \%$		1,00	0,34	-0,33		1,00	0,72	0,54
	$m_{ms}, \%$			1,00	0,68			1,00	0,84
	$m_{OH}, \%$				1,00				1,00



$m_l$  – loosely bound water of the colloid surface;  $m_s$  – strongly bound water of the colloid surface;  $m_{ms}$  – water of the mineral surface and the hydration of ions;  $m_{OH}$  – water of the hydroxyl groups in the mineral .

In Grade 1 of the kaolinite clay there are statistical links between the mass loss of the loose bound colloid water ( $r = 0.82 > r_k = 0.81$ ) and pressure. In Grade 2 statistical links are determined only between the pressure and  $m_{OH}$  ( $r = -0.83 > r_k = 0.71$ ).

So, we can conclude that the formation of loose bound colloid water is controlled by the pressure of up to  $P < 1000$  MPa, and hydroxyl groups water in the crystal  $P > 1000$  MPa. The data show that, first, the pressure has less influence on the formation of water in the kaolinite clay than montmorillonite. Secondly, the conditions of formation of water in the kaolinite, both at the level of the colloid ( $m_s$ ), and crystal ( $m_{ms}$ ) are fundamentally different from the conditions of formation of these waters in montmorillonite. This is proved by the positive and negative number signs of the correlation coefficients, which reflect the type of the relationship between  $P$  and  $m$  (Fig.4).

Under the conditions of the experiment, the parameter indicating the mass loss of the substance should be interpreted as an indicator of the sorption activity of the clays subjected to compression because the clay sample was subjected to compression, and then the soil sample was hold for 35-40 days indoors at the temperature  $t = 24 \div 26^\circ\text{C}$ . This procedure made possible to stabilize the process of water adsorption by

the clay from the air. Then thermal analysis was applied. The obtained data allowed estimate the mass loss of the substance in the clay at heating.

The change of montmorillonite and kaolinite clays sorption activity is probably due to changes in the structure of clay particles, the crystal lattice of minerals and the formation of additional active centers on their surface. Consider this problem in more detail.

The most significant influence on sorption properties of kaolinite clay has the degree and order of layers packing and the defects like random translations of the adjacent layers increase the physical-chemical activity of kaolinite.

As criteria of clays physical-chemical activity Shlykov V. G. proposed an indicator «area of coherent scattering» (ACS) of x-rays in the direction of the axis  $c$  [Shlykov, 2000]. It correlates with the particles structure (micro blocks) and their sorption activity. Low values of ACS indicate that micro blocks are small and consist of strictly parallel elementary layers, therefore kaolin is characterized by high values of cation exchange capacity. In addition it is marked out that at low values of ACS water molecules occur between micro blocks and facilitate the random offset of sub-packings relatively to each other, which leads to a sharp increase in sorption activity of the particles.

The presented data show that interlunar distance in kaolinite and montmorillonite clays increases with the pressure increase and integral intensity of basal reflection decreases (Table 4).

Table 4. Results of clay diffractometric analysis

Clay	Load, (pressure) MPa	Diffraction Angle, $2\Theta$	Interplanar Distance, $d, \text{\AA}$	Half-width of basal reflection, $B/2$	Peak area intensity of basal reflection)	Average values of bound water mass loss, %			
						$m_l$	$m_s$	$m_{ms}$	$m_{OH}$
Montmorillonite clay	0	12,474	7,091	0,442	0,431	4,80	0,80	3,60	2,10
	1000	12,424	7,119	0,402	0,446	5,55	1,00	5,40	4,20
	1500	12,443	7,108	0,471	0,316	5,30	0,85	3,10	2,30
	2000	12,428	7,116	0,617	0,358	6,00	1,10	7,10	5,18
Kaolinite clay	0	12,344	7,165	0,377	3,895	2,10	0,295	8,07	1,913
	1000	12,350	7,161	0,430	3,495	5,545	0,325	5,370	0,635
	1500	12,299	7,191	0,577	2,283	3,765	1,060	8,675	2,310
	2000	12,286	7,199	0,564	2,522	3,375	0,610	7,010	0,720

$m_l$  – loosely bound water of the colloid surface;  $m_s$  – strongly bound water of the colloid surface;  $m_{ms}$  – water of the mineral surface and the hydration of ions;  $m_{OH}$  – water of the hydroxyl groups in the mineral.

Therefore, the sorption capacity of kaolinite clays, expressed by the index  $m$ , decreases. High sorption properties of montmorillonite clays are provided by the dispersity and defectiveness of the structure. It is known that the type and valence of exchangeable cations would not significantly affect the process of intra-crystalline swelling in clays, but in colloids, on the contrary, are the determining factors. So, the number of exchange centers located on the outer surface of the particles can reach 60-70% of the total exchange capacity. The presence of defects in the packing of layers increases this ratio in favor of the "external reservoir". Published data do not contradict the results of our experiment, as evidenced by

statistical link between pressure and mass loss of strongly bound and loosely bound colloid water (Table 3).

Thus, we can assume that at the compression of clay, on the one hand, there take place the processes of clay particles consolidation, which should lead to a decrease in sorption capacity of the clay. On the other hand, with pressure increase the structure of clay particles (lattice structure) changes and stimulates the formation of additional active centers on the crystal and colloid surface causing the increase in sorption capacity of the clays and, as a consequence, the increase in bound water mass loss.

The presence of the established patterns suggests that under

conditions of our experiment, the main factor determining the bound water mass loss is the change in the structure of clay particles and the structure of the montmorillonite crystal lattice, whereas, the size of clay particles has a subordinate (secondary) value.

The presence of statistical links allowed calculate the equations of the relationship. The following mathematical models are obtained for the montmorillonite clays:

$$\text{Grade 1 } m_l = 4.5185 + 0.0015P$$

$$\text{Grade 1 } m_s = 0.7865 + 0.0006P$$

$$\text{Grade 2 } m_{ms} = -12.2217 + 0.0097P$$

$$\text{Grade 2 } m_{OH} = -7.1682 + 0.0061P$$

The following mathematical models are obtained for the kaolinite clays:

$$\text{Grade 1 } m_l = 1.9696 + 0.0032P$$

$$\text{Grade 2 } m_{OH} = 7.0512 - 0.0031P$$

## III. CONCLUSIONS

1. It was established experimentally that in the studied soils with pressure increase up to  $P=2000\text{MPa}$  there is a decrease of clay fraction.

2. Study of substance mass loss at compression of clays to  $P=2000\text{MPa}$  showed that there are two selection groups: the pressure boundaries determining the formation of the kaolinite clays fractional composition are in the range  $P=600\div1000\text{MPa}$  and montmorillonite clays  $P=1000\div1500\text{MPa}$ .

3. The experimental studies showed that in the kaolinite clay with pressure increase the mass loss of bound water decreases, and in the montmorillonite clays, on the contrary, it increases.

4. Mathematical models have been built to predict the bound water mass loss in clays depending on the applied load.

Thermogravimetric analysis of clay samples were carried out on the equipment of the nanomineralogy Sector of Perm State National Research University under the leadership of Professor Osovetsky B. M, to whom the authors express their deep gratitude.

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